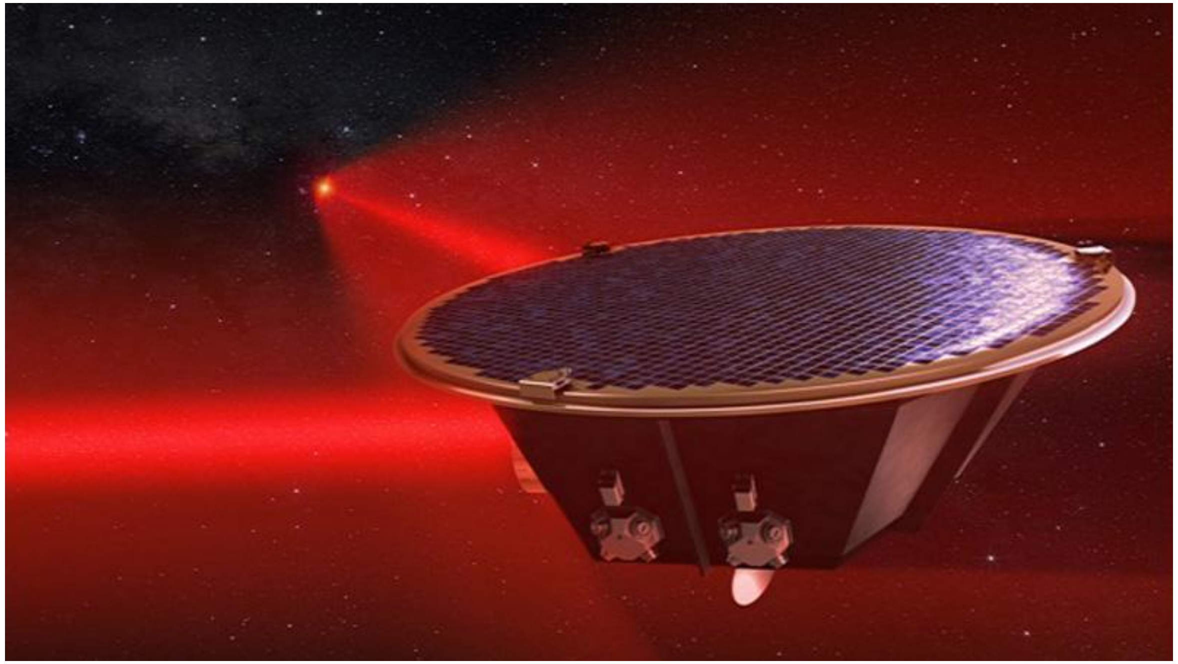
UniTN PPW 2020
December 2, 2020

Space-based gravitational wave detection: experimental challenges

– Physics PhD Workshop 2020 –

Lorenzo Sala – UTN LISA Group

University of Trento, December 2, 2020



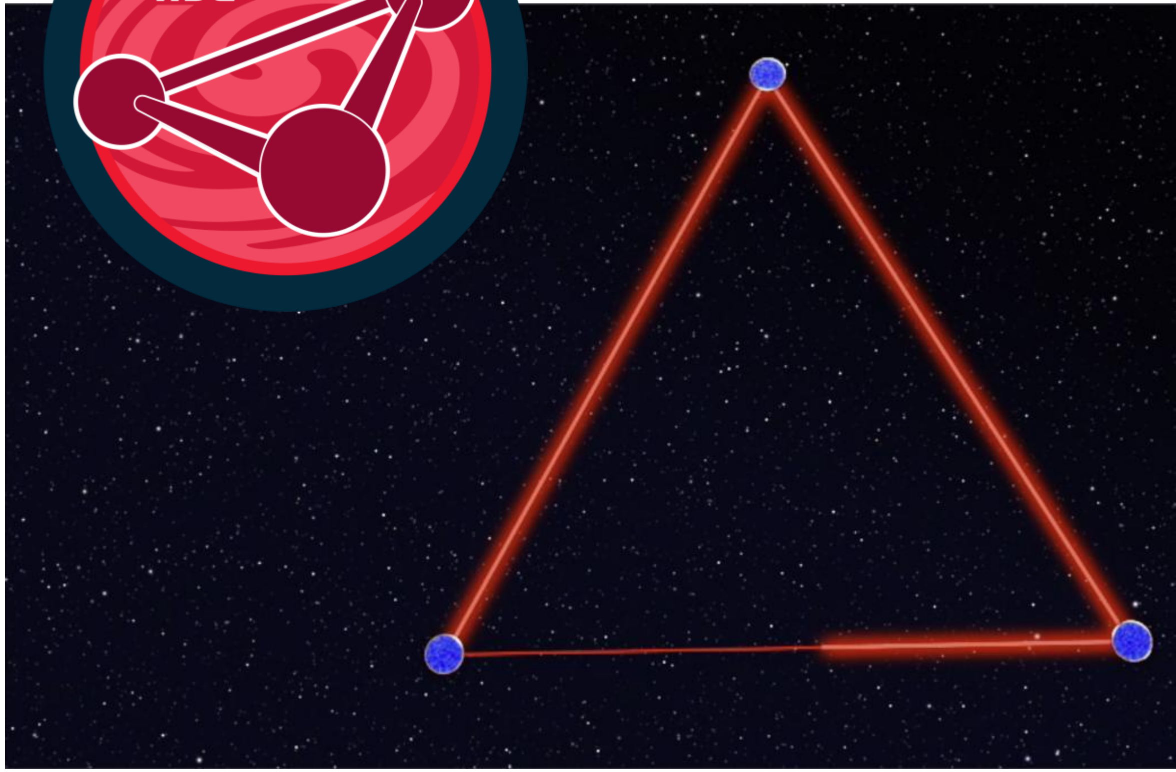
UNIVERSITÀ DI TRENTO

Agenzia Spaziale Italiana

INFN

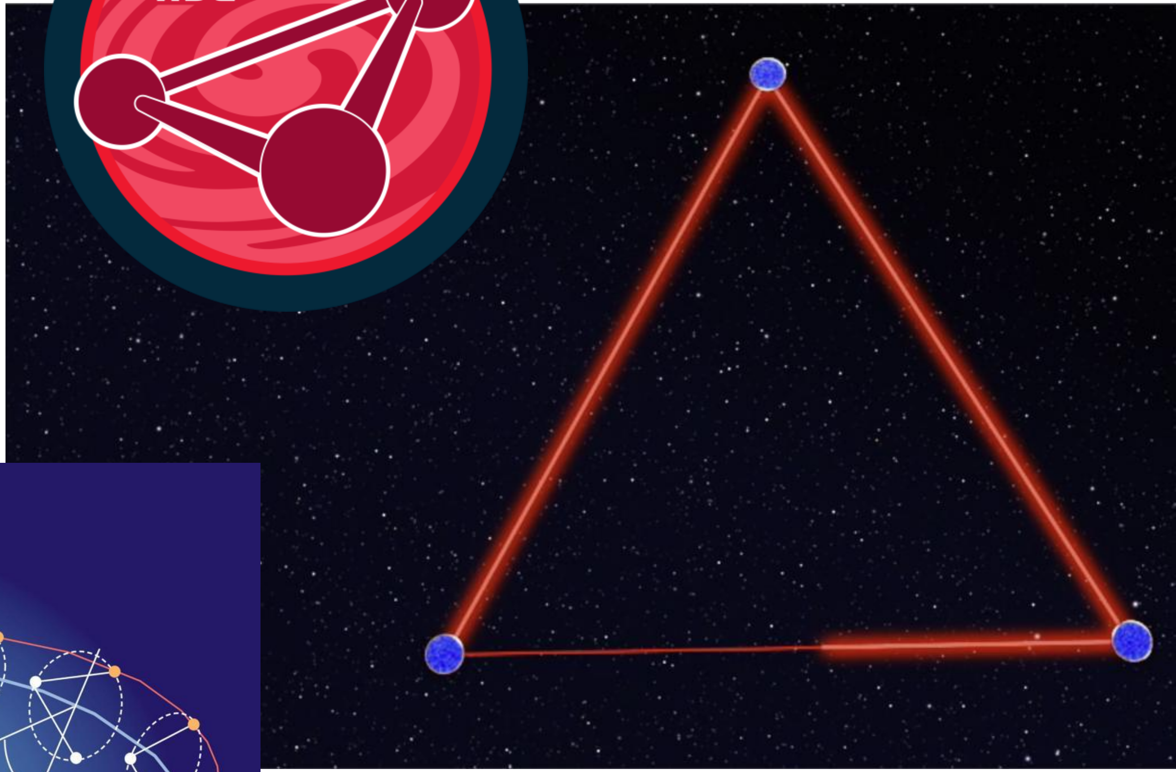
Space-based GW observation

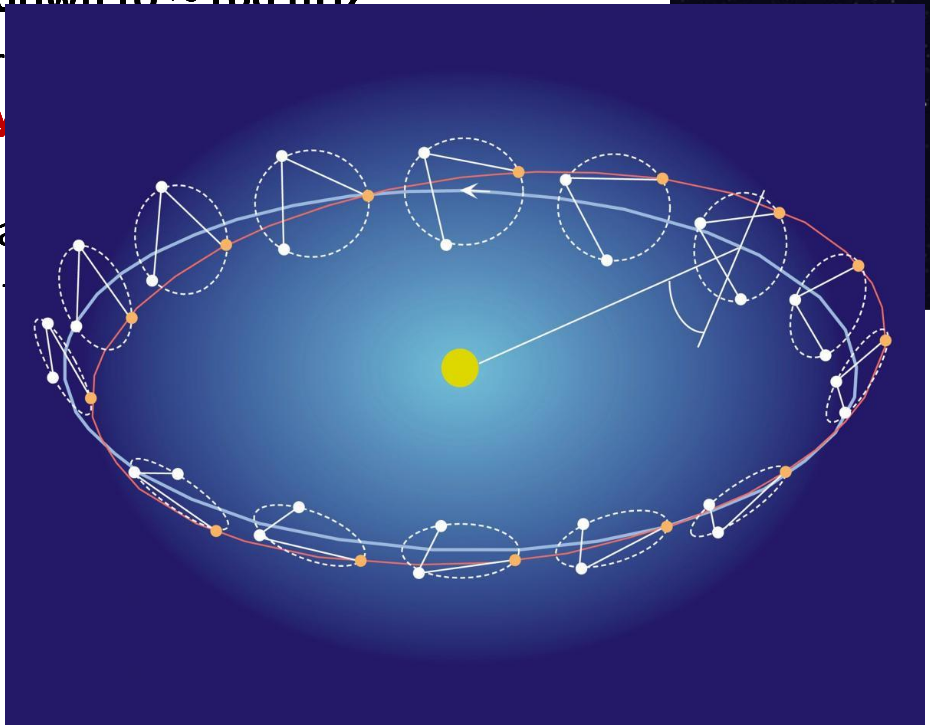
- Planned for launch in 2034, LISA will be able to detect **sub-Hz Gravitational Waves** (GW):
  - The three-arm constellation **will orbit the Sun** in an Earth-trailing orbit, smoothly changing its orientation.
  - The chosen **2.5-million km armlength** will allow for the required sensitivity to the gravitational strain within the sensitive frequency band, **down to ~100 μHz**.
  - The complex interferometric system will detect GWs as the time-varying **frequency Doppler shift** between the emitted and received laser beams.
  - To cope with the solar radiation pressure fluctuations, laser beams will bounce off free-falling **2kg Gold-Platinum Test-Masses (TM).**



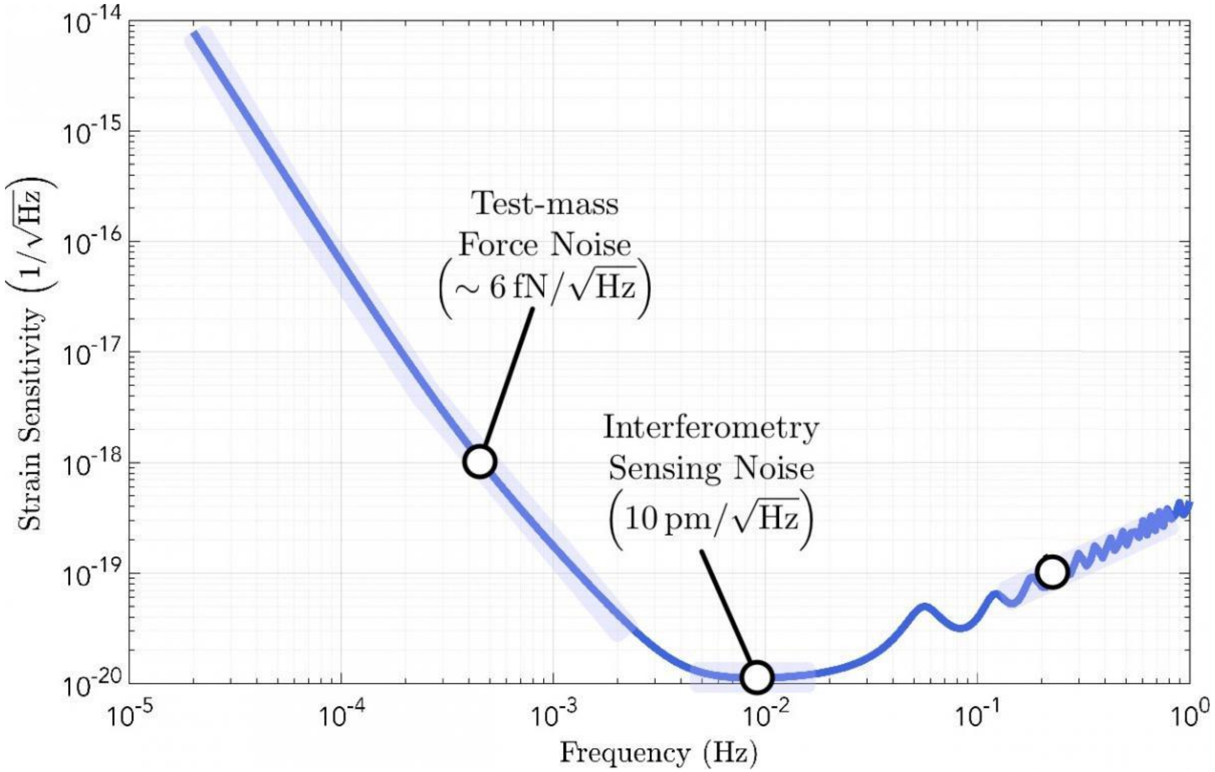
Space-based GW observation

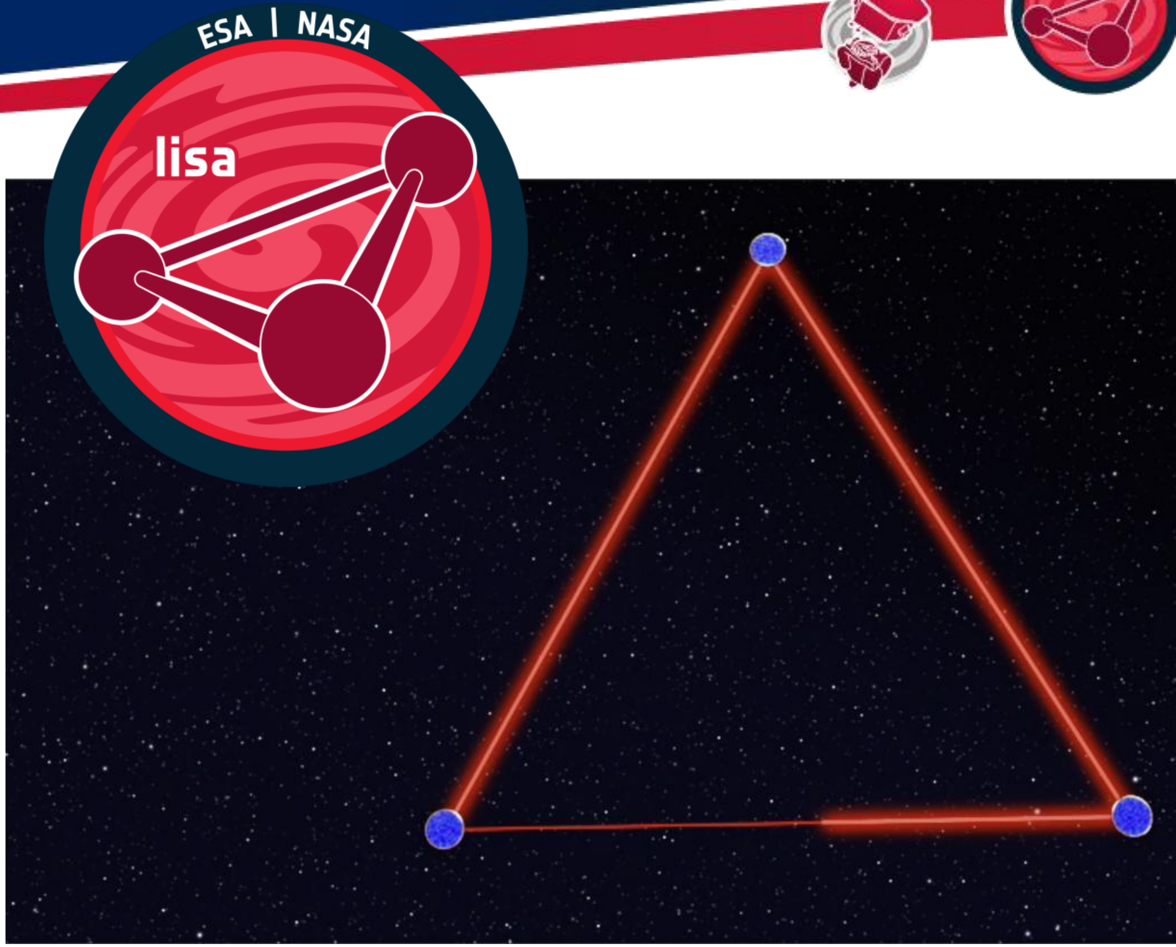
- Planned for launch in 2034, LISA will be able to detect **sub-Hz Gravitational Waves** (GW):
  - The three-arm constellation **will orbit the Sun** in an Earth-trailing orbit, smoothly changing its orientation.
  - The chosen **2.5-million km armlength** will allow for the required sensitivity to the gravitational strain within the sensitive frequency band, **down to ∼100 μHz**
  - The complex interferometr the time-varying **frequency** emitted and received laser
  - To cope with the solar radia beams will bounce off free- **Test-Masses (TM).**





Space-based GW observation



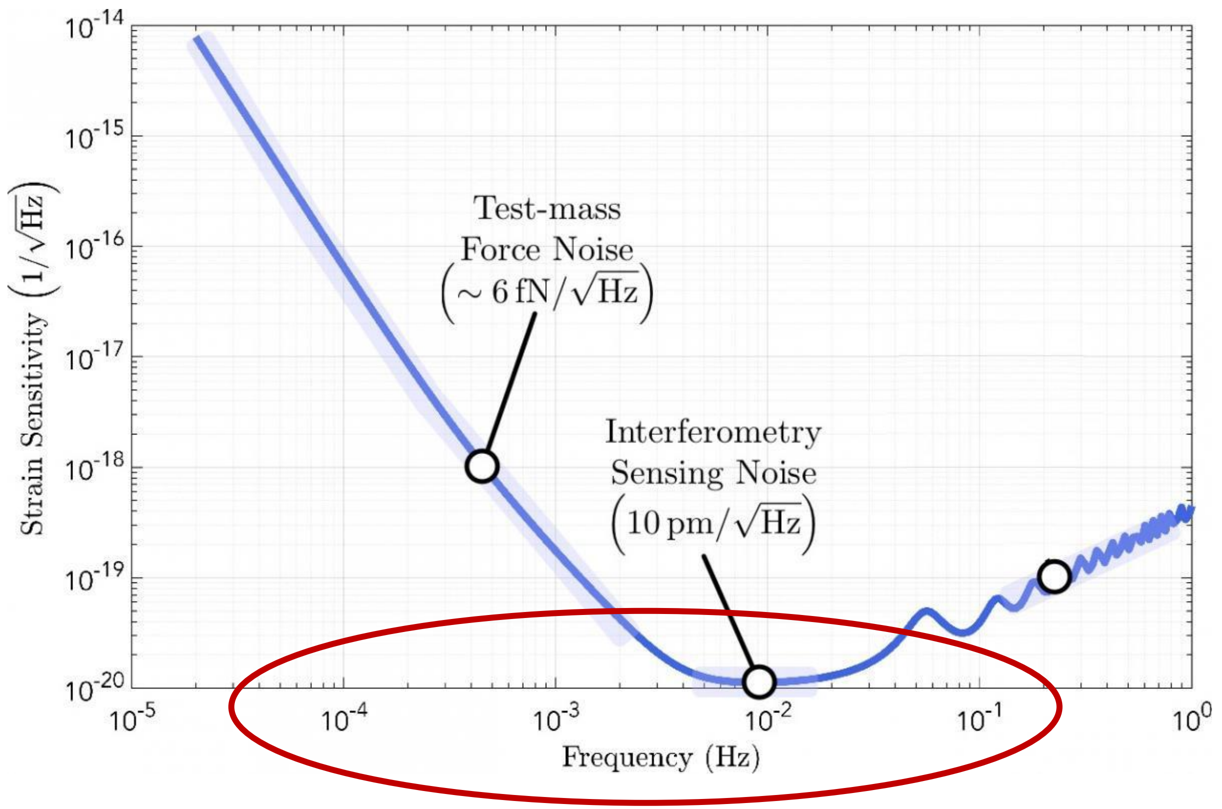


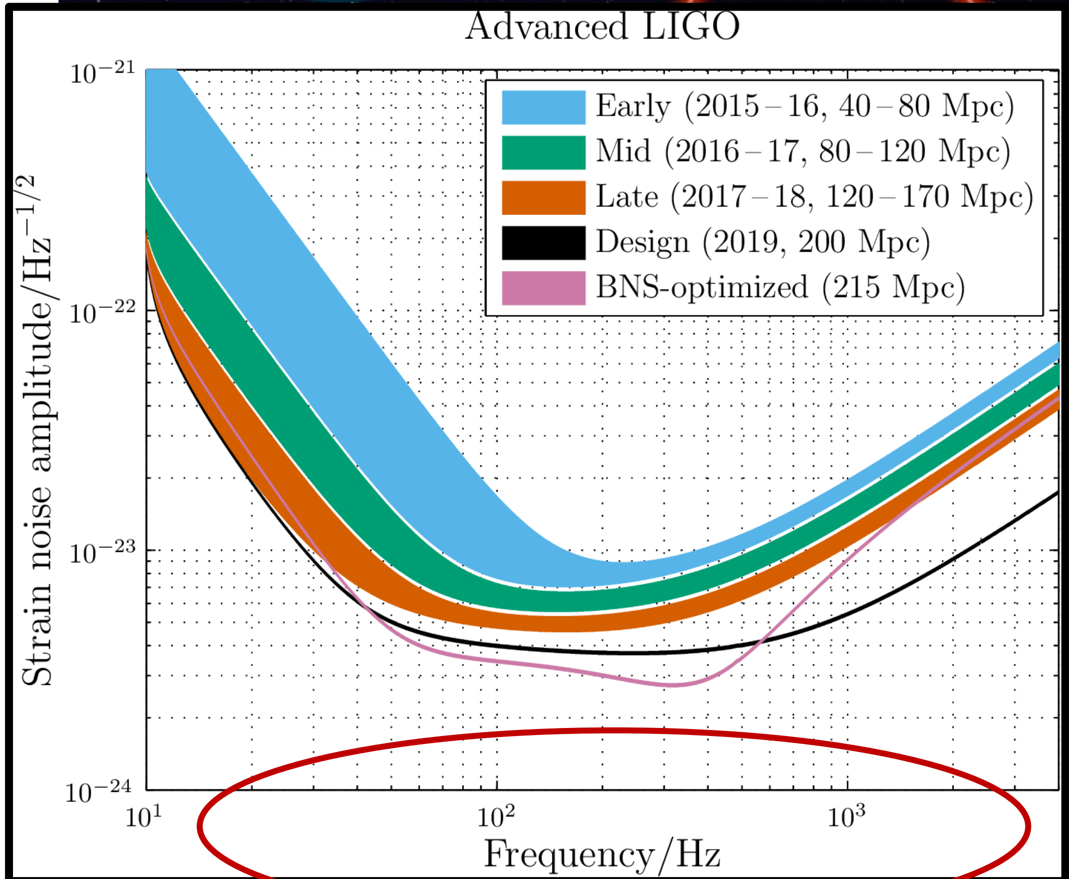
UNIVERSITÀ DI TRENTO

Agenzia Spaziale Italiana

INFN

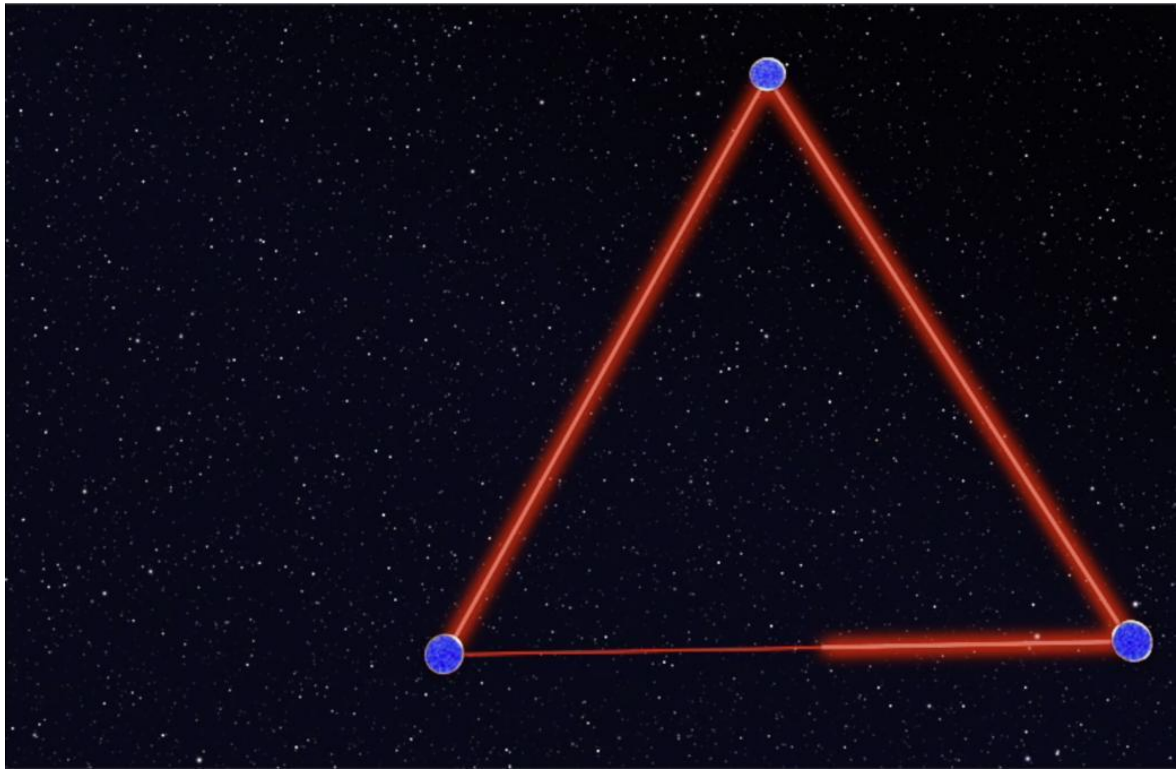
Space-based GW observation





Space-based GW observation

- Planned for launch in 2034, LISA will be able to detect **sub-mHz Gravitational Waves** (GW):
  - The three-arm constellation **will orbit the Sun** in an Earth-trailing orbit, smoothly changing its orientation.
  - The chosen **2.5-million km armlength** will allow for the required sensitivity to the gravitational strain within the sensitive frequency band.
  - The complex interferometric system will detect GWs as the time-varying **frequency Doppler shift** between the emitted and received laser beams.
  - To cope with the solar radiation pressure fluctuations, laser beams will bounce off free-falling **2kg Gold-Platinum Test-Masses (TM).**



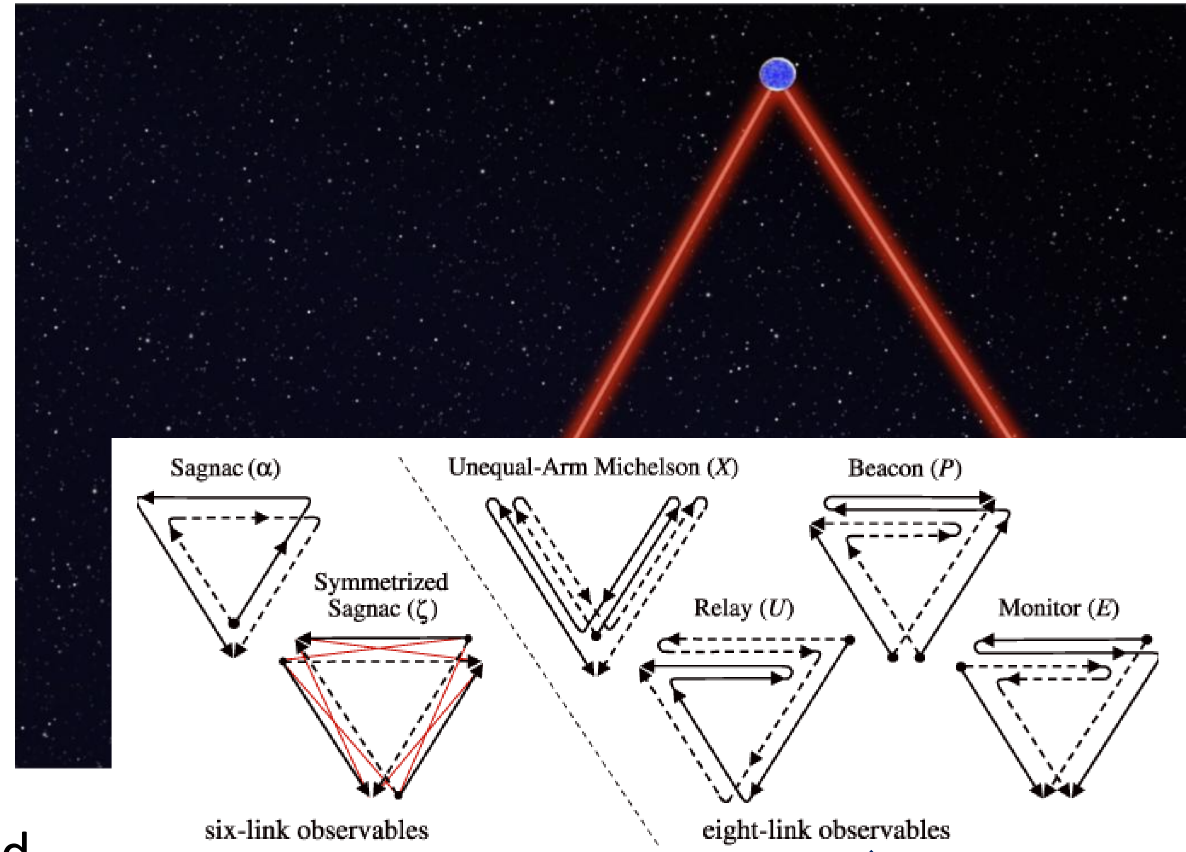
- **Force noise** acting on the TMs, **phase-meter noise** and **laser frequency fluctuation noise** will mimic the GW behavior.

$$\frac{\Delta\dot{\nu}}{\nu_0} = \underbrace{\frac{1}{2}\left(\dot{h}\left(t - \bar{n}_{GW} \cdot \frac{\bar{r}}{c}\right) - \dot{h}(t)\right)}_{\text{GW}} + \frac{1}{c}\underbrace{\left(a_e\left(t - \frac{L}{c}\right) - a_r(t)\right)}_{\text{Acc.}} + \frac{\delta\dot{\nu}_{meas}(t)}{\nu_0} + \frac{\delta\dot{\nu}_{laser}\left(t - \frac{L}{C}\right)}{\nu_0}$$

UNIVERSITÀ DI TRENTO
Agenzia Spaziale Italiana
INFN

Space-based GW observation

- Planned for launch in 2034, LISA will be able to detect **sub-mHz Gravitational Waves** (GW):
  - The three-arm constellation **will orbit the Sun** in an Earth-trailing orbit, smoothly changing its orientation.
  - The chosen **2.5-million km armlength** will allow for the required sensitivity to the gravitational strain within the sensitive frequency band.
  - The complex interferometric system will detect GWs as the time-varying **frequency Doppler shift** between the emitted and received laser beams.
  - To cope with the solar radiation pressure fluctuations, laser beams will bounce off free-falling **2kg Gold-Platinum Test-Masses (TM).**



TDI – Time-Delay Interferometry

- **Force noise** acting on the TMs, **phase-meter noise** and **laser frequency fluctuation noise** will mimic the GW behavior.

$$\frac{\Delta\dot{\nu}}{\nu_0} = \frac{1}{2}\left(\dot{h}\left(t-\bar{n}_{GW}\cdot\frac{\bar{r}}{c}\right)-\dot{h}(t)\right)+\frac{1}{c}\left(a_e\left(t-\frac{L}{c}\right)-a_r(t)\right)+\frac{\delta\dot{\nu}_{meas}(t)}{\nu_0}+\frac{\delta\dot{\nu}_{laser}\left(t-\frac{L}{C}\right)}{\nu_0}$$

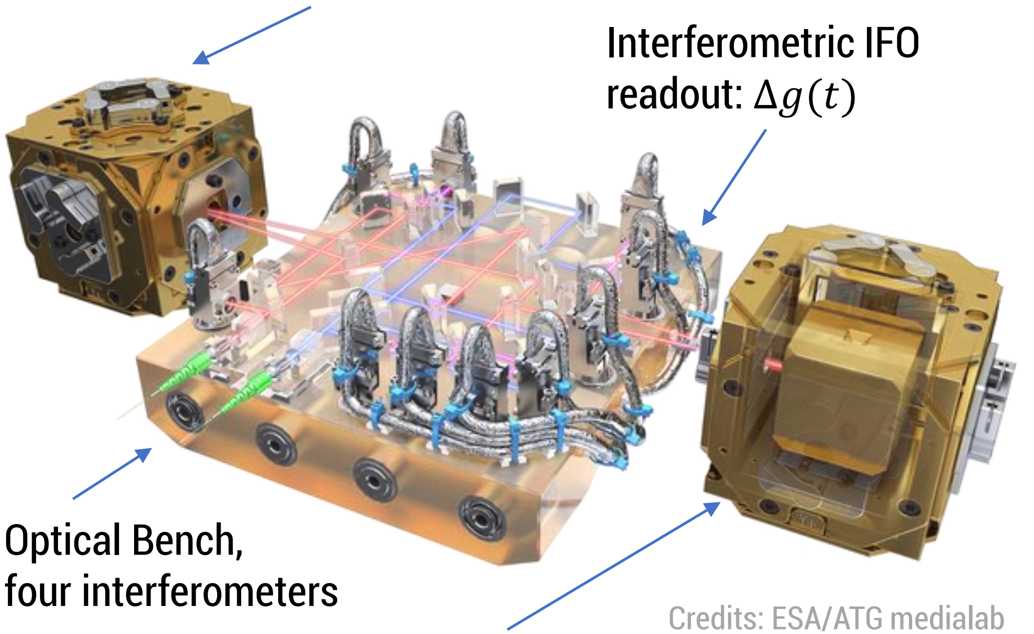
UNIVERSITÀ DI TRENTO

Agenzia Spaziale Italiana

INFN

Force noise and LISA Pathfinder

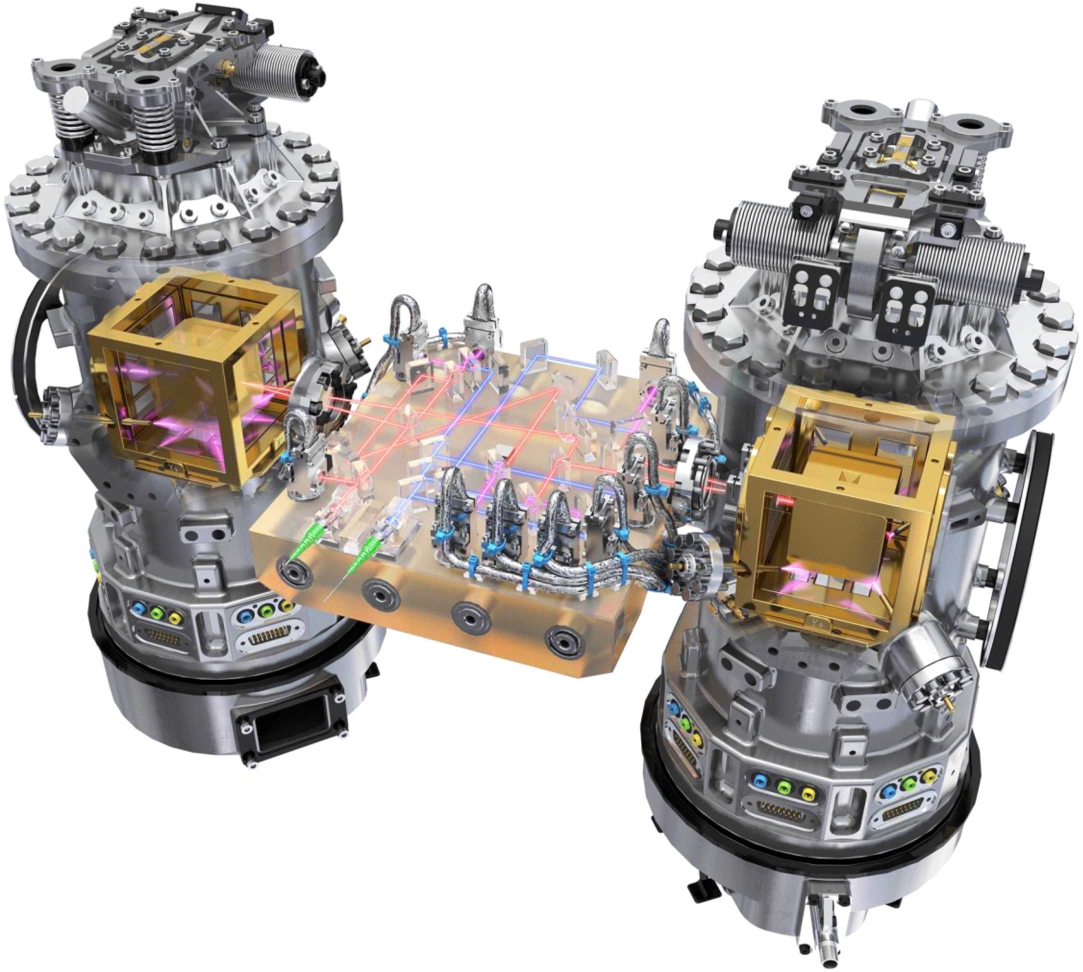
- The noise performance was investigated in the **LISA Pathfinder (LPF)** Mission, launched in 2015 and completed in 2017.
  - Demonstration mission: **first sub-pm IFO flown** in space, hardware testing, drag-free control technology testing, etc.
  - Main scientific measurement: the **out-of-loop differential acceleration** between two LISA-like Gold-Platinum TM, along a "shrunk" 38cm LISA arm.
  - The TMs were caged in **Electrode Housings**, that provided a capacitive position readout (GRS) and a force feedback, to close the measurement loop and keep the system linear.
  - Need for positioning control loop, actuation forces on TM1, TM2. Actuation forces along sensitive axis on TM2.
  - UV photoelectric discharge.



Credits: ESA/ATG medialab

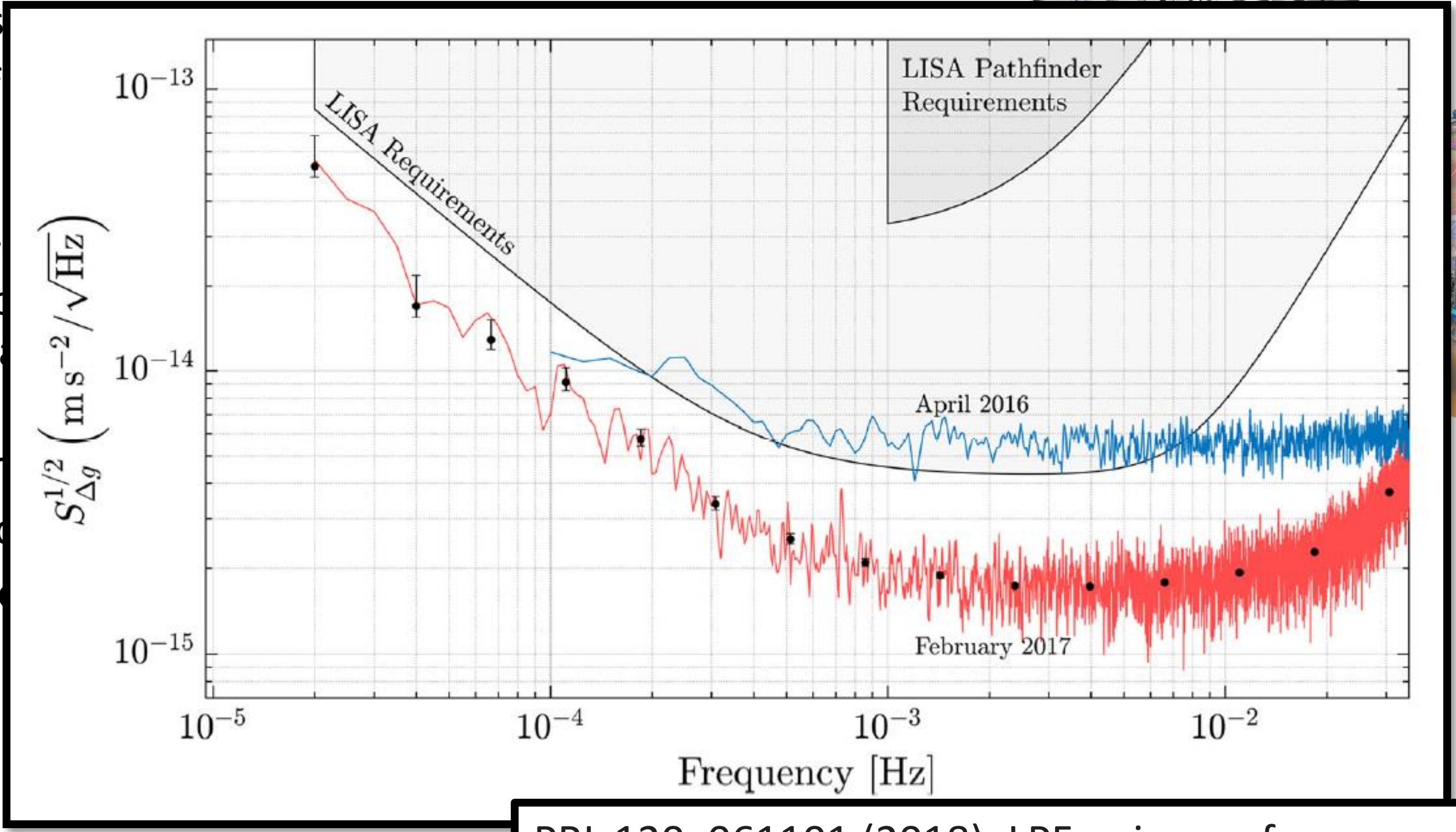
Force noise and LISA Pathfinder

- The noise performance was investigated in the **LISA Pathfinder (LPF)** Mission, launched in 2015 and completed in 2017.
  - Demonstration mission: **first sub-pm IFO flown** in space, hardware testing, drag-free control technology testing, etc.
  - Main scientific measurement: the **out-of-loop differential acceleration** between two LISA-like Gold-Platinum TM, along a “shrunk” 38cm LISA arm.
  - The TMs were caged in **Electrode Housings**, that provided a capacitive position readout (GRS) and a force feedback, to close the measurement loop and keep the system linear.
  - Need for positioning control loop, actuation forces on TM1, TM2. Actuation forces along sensitive axis on TM2.
  - UV photoelectric discharge.
  - Vacuum Enclosures independently sealed and vented to space.

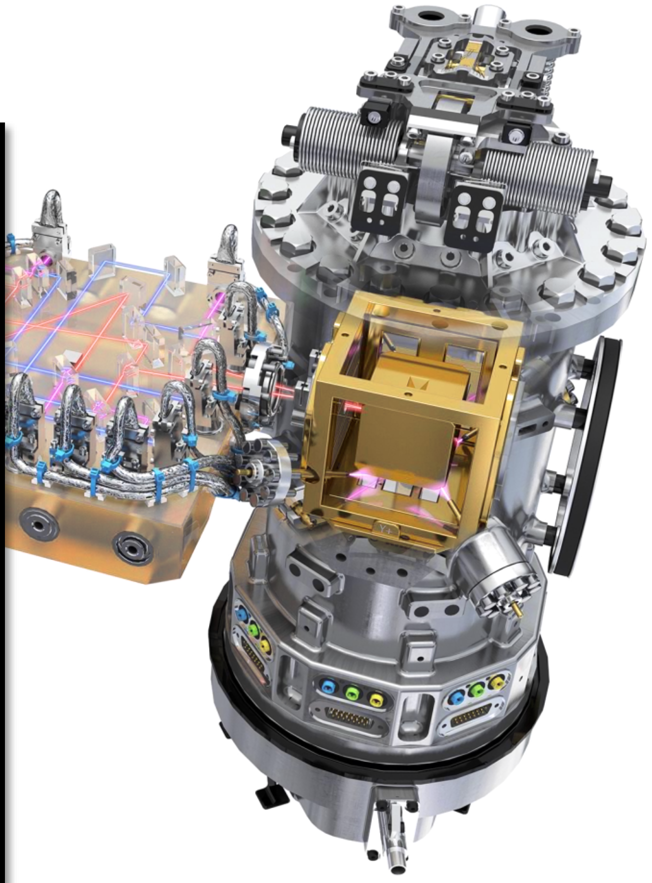


Force noise and LISA Pathfinder

- The noise performance was investigated in the **LISA Pathfinder (LPF)** Mission, launched in 2015 and completed in 2017.
  - Demonstration mission: **first sub-pm IFO ever flown** in space, hardware tes
  - Main scientif **acceleration** 38cm LISA ar
  - The TMs wer a capacitive p close the mea
  - Need for pos Actuation for
  - UV photoelec
  - Vacuum Encl



PRL 120, 061101 (2018), LPF noise performance



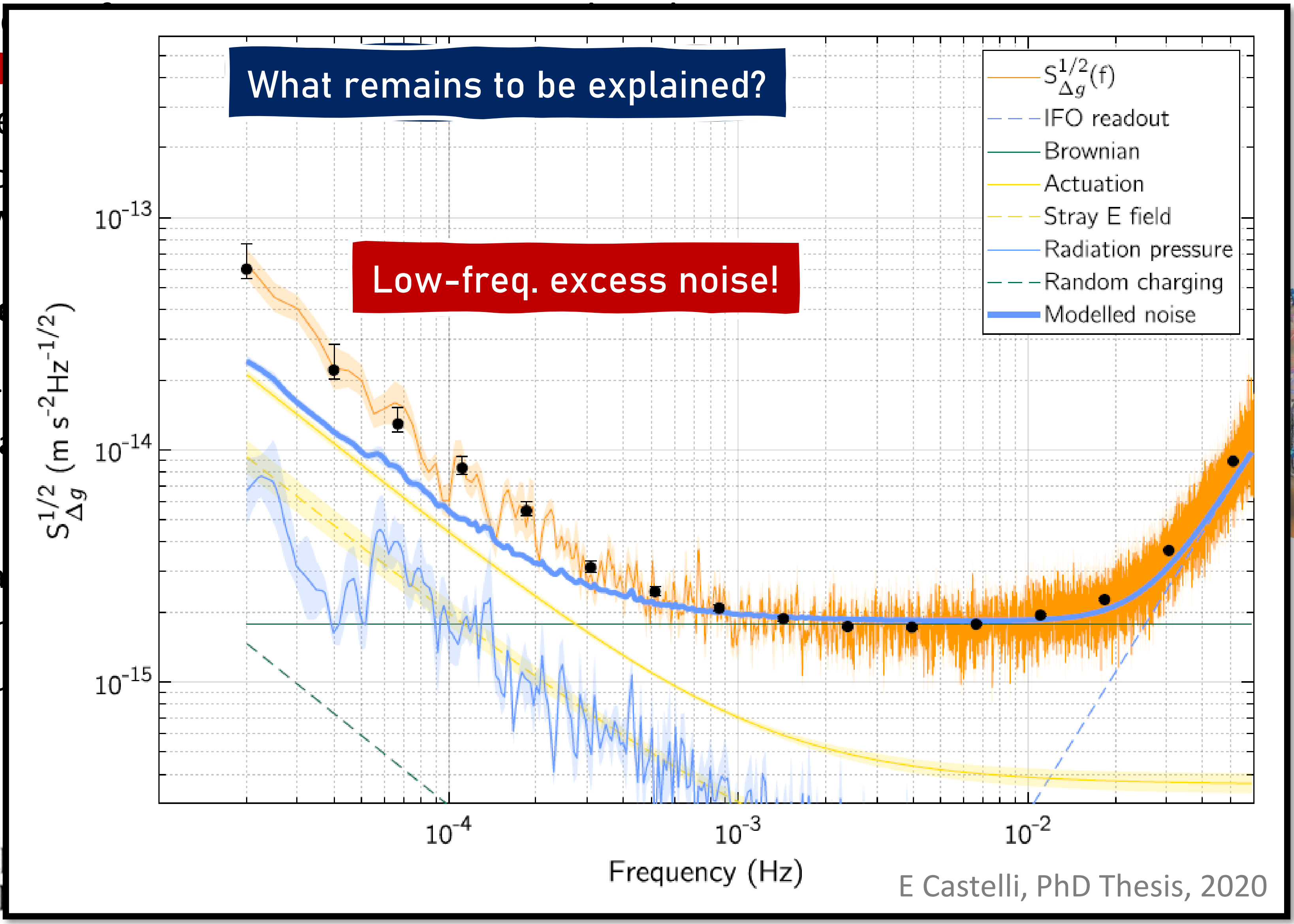
UNIVERSITÀ DI TRENTO

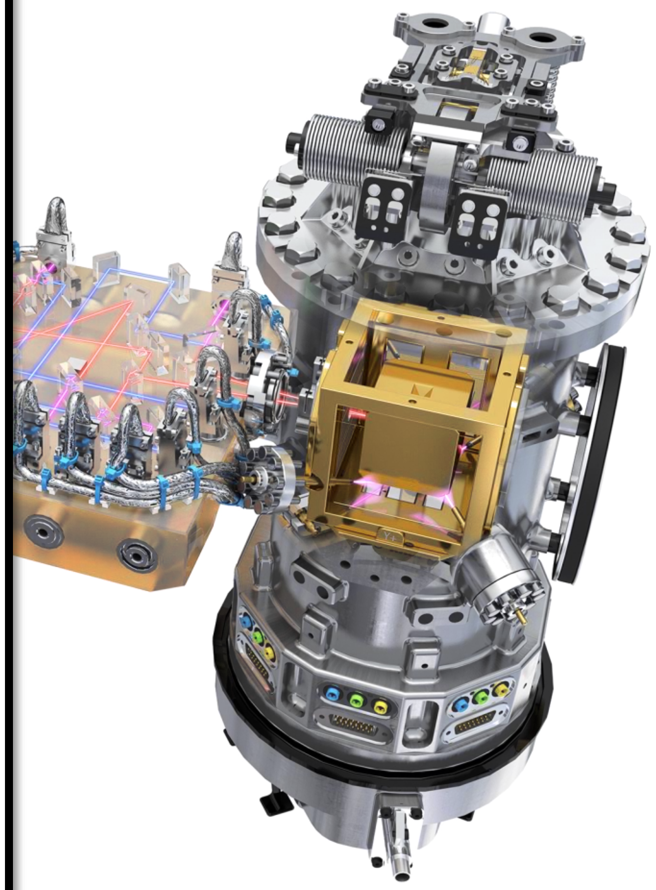
Agenzia Spaziale Italiana

INFN

Force noise and LISA Pathfinder

- The nois
  LISA Pat
  complete
  - Demo
    hardw
  - Main
    accel
    38cm
  - The T
    a capa
    close
  - Need
    Actua
  - UV ph
  - Vacuu

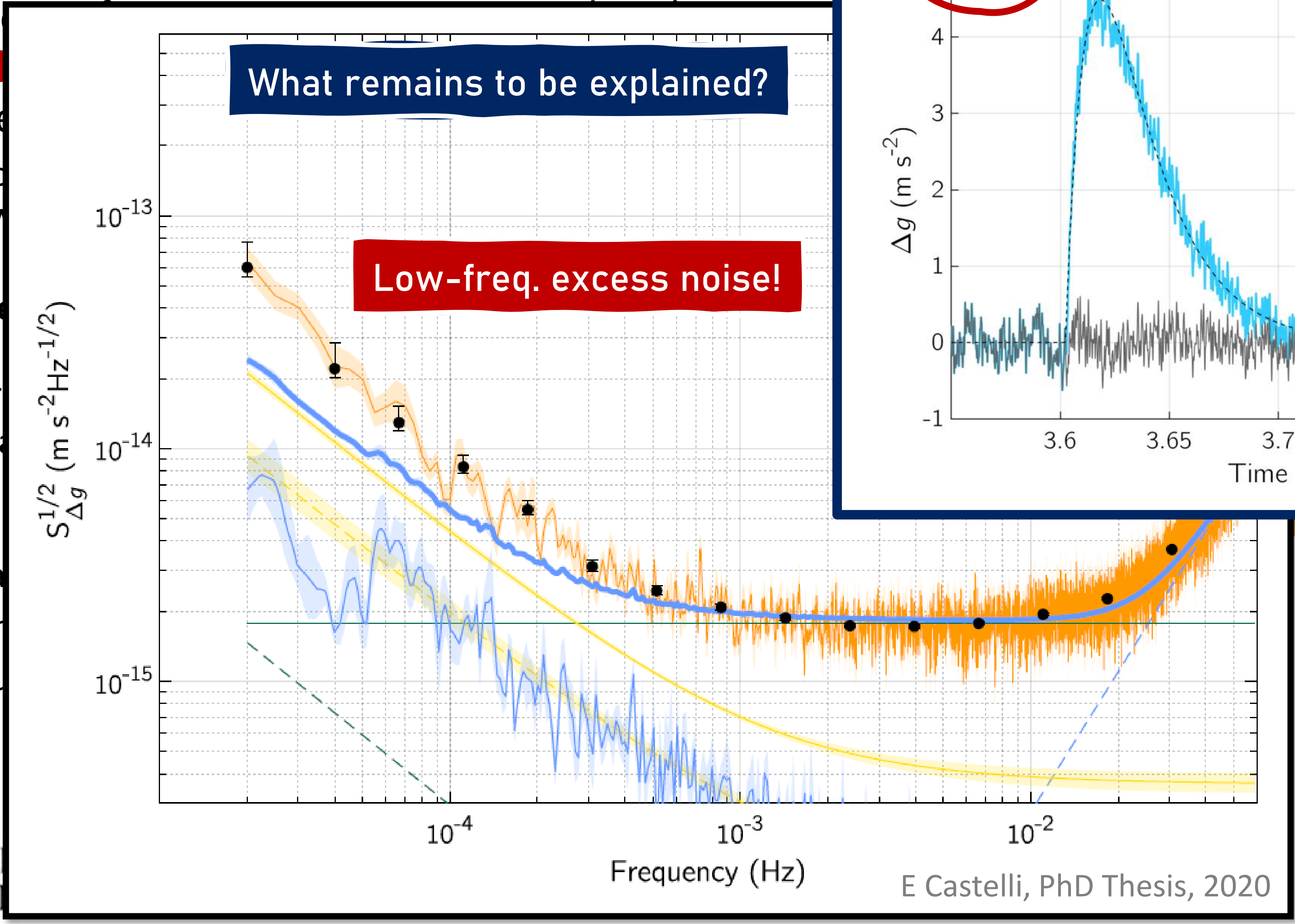




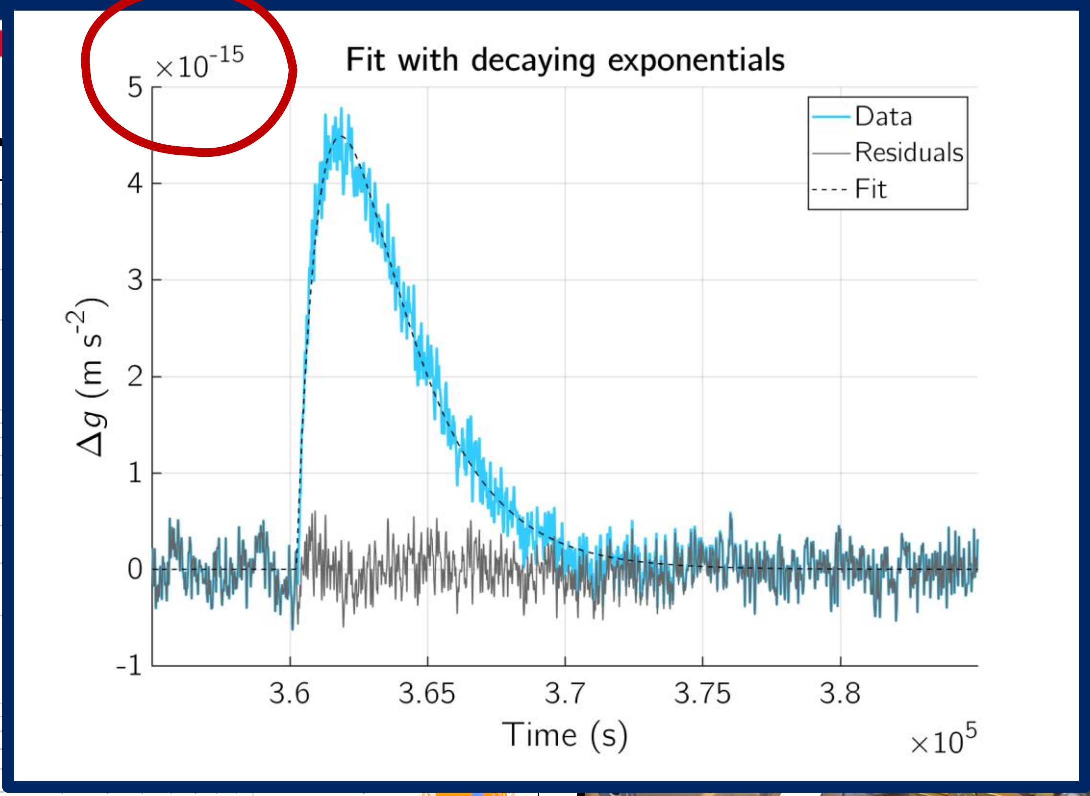
Force noise and LISA Pathfinder

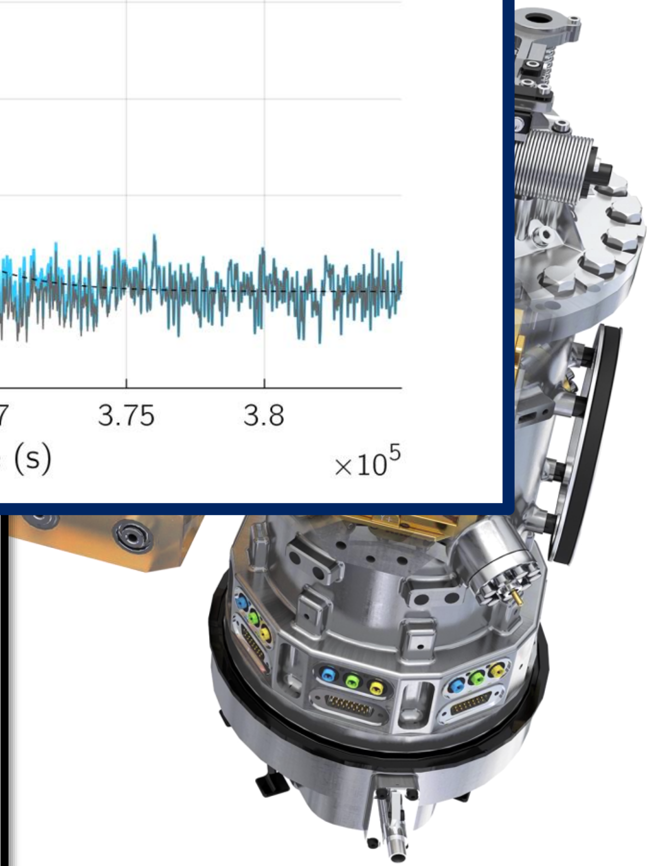
Femto-Newton glitches!

- The nois
  LISA Pat
  complete
  - Demo
    hardw
  - Main
    accel
    38cm
  - The T
    a capa
    close
  - Need
    Actua
  - UV ph
  - Vacu



E Castelli, PhD Thesis, 2020

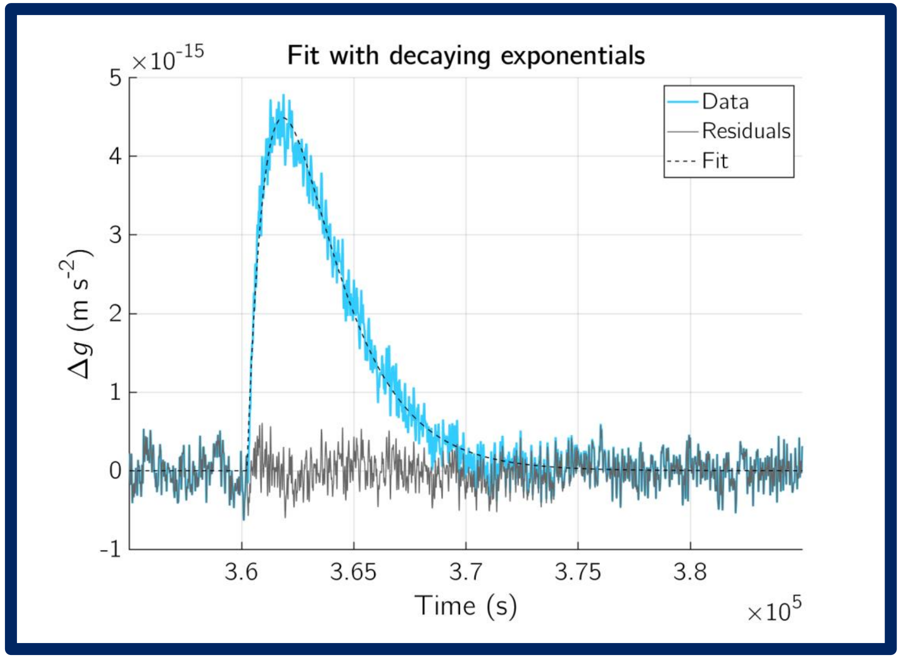




UNIVE
DI TRE

Spurious events “glitches” on LPF

- Detected as differential acceleration peaks. Unknown nature.
- **Pure force** events along IFO-axis, with **no torque counterpart.***
- **Wide range of duration:** ~seconds to **hours**.
- The strongest ones are measured both by IFO and GRS.
- No magnetic anomalies, no micrometeorites, no spurious voltages, no laser intensity fluctuations, no external sources.
- Rate **reversibly increased** after lowering temperature to 0°C.
- A deeper understanding of their origin could help design and forecasts on LISA.



Which source meets
all the measured properties?

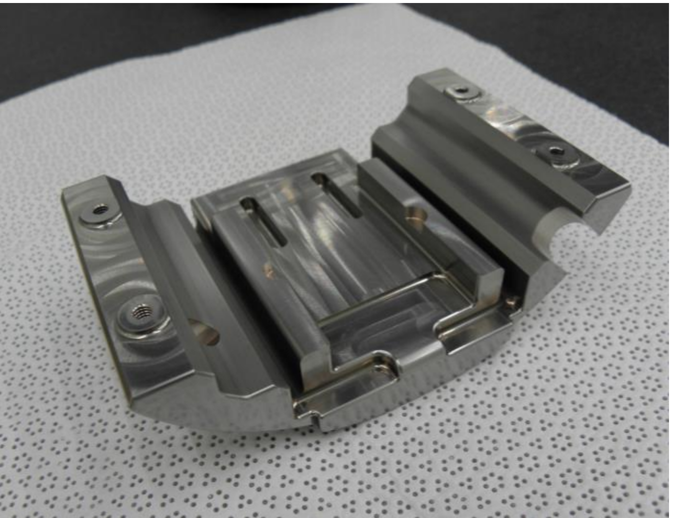
* Phys. Rev. Lett. **120**, 061101(2018)

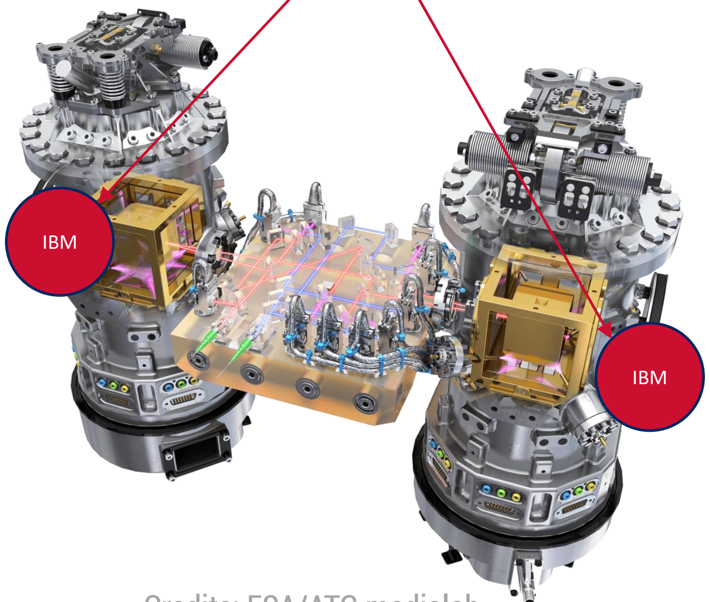
UNIVERSITÀ DI TRENTO

Agenzia Spaziale Italiana INFN

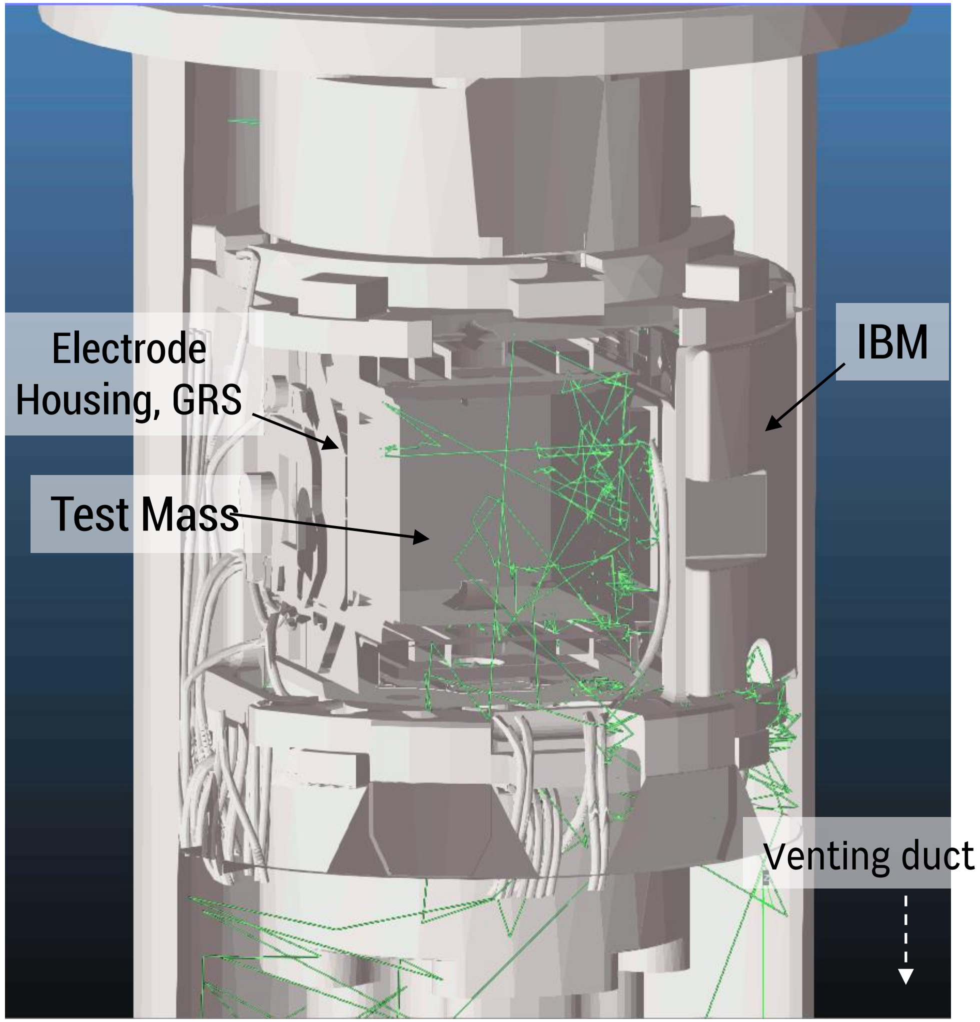
Glitches as outgassing events

- Highly likely source: **outgassing gas bursts** from pores.
  - Long-lasting timescale: molecular dynamics in pores.
  - No overall torque: molecules entering Electrode Housing through x-axis holes.
  - Rate increased at low temperature: mechanical stress.
  - First candidate: Internal Balance Mass (IBM), made of (porous?) tungsten/copper 90/10 alloy.



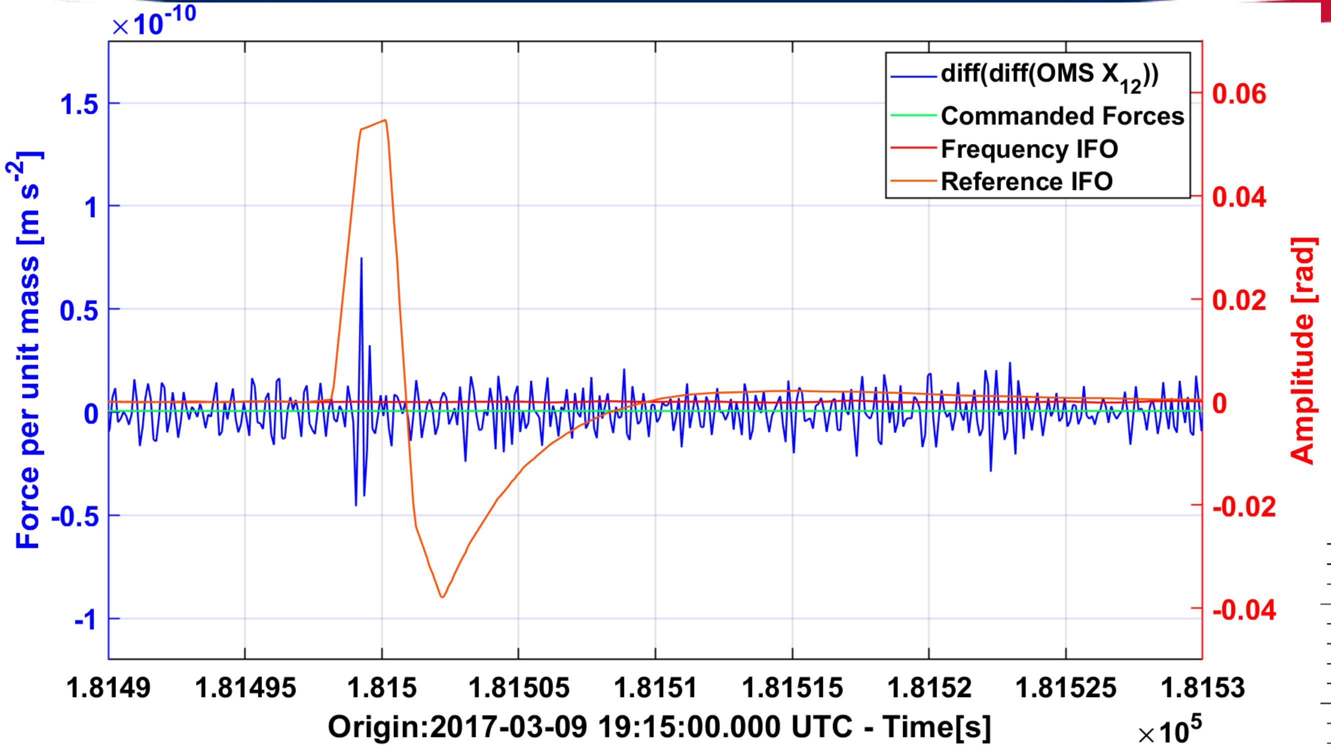


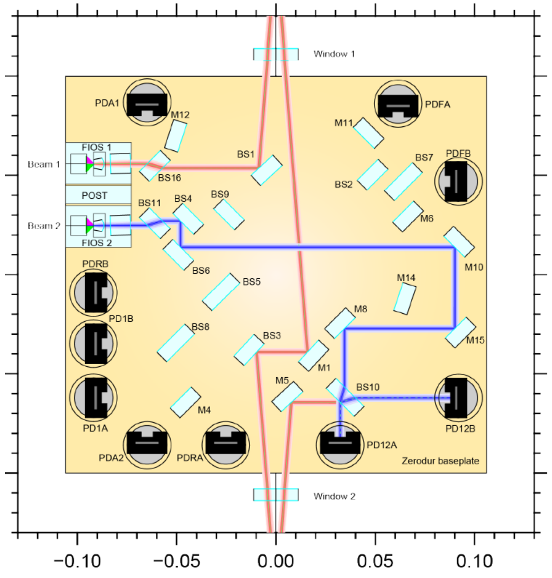
Credits: ESA/ATG medialab

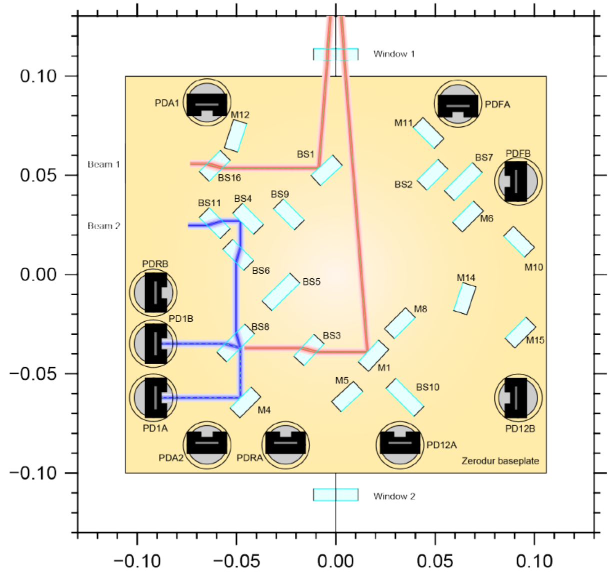


Molecular simulation of impulsive emission from IBM, front-side, LPF geometry. [Design courtesy: OHB Italia SpA]

Interferometer glitches?







UNIVERSITÀ DI TRENTO

Agenzia Spaziale Italiana

INFN

Conclusions

- The **LISA Mission** will detect gravitational waves in the low-frequency spectrum, in the next decades. LISA is currently in its development Phase A.
- **LISA Pathfinder** exceeded its requirements, showing that space is the right place for the detection of low-frequency GWs.
- Research is still going on about features of the LPF noise:
  - Excess **low-frequency noise**, whose origin is still unknown.
  - **One-sided glitches** could be explained as outgassing bursts striking the Test-Masses, but there are **several open questions** that need to be answered.
  - **Two-sided** quick glitches might be due to events in the interferometric readout, but their true origin still needs to be assessed.
  - Research is going on, to carefully forecast the noise performance of the LISA Mission.

Our new UTN LISA website is being set up these days! Coming soon!